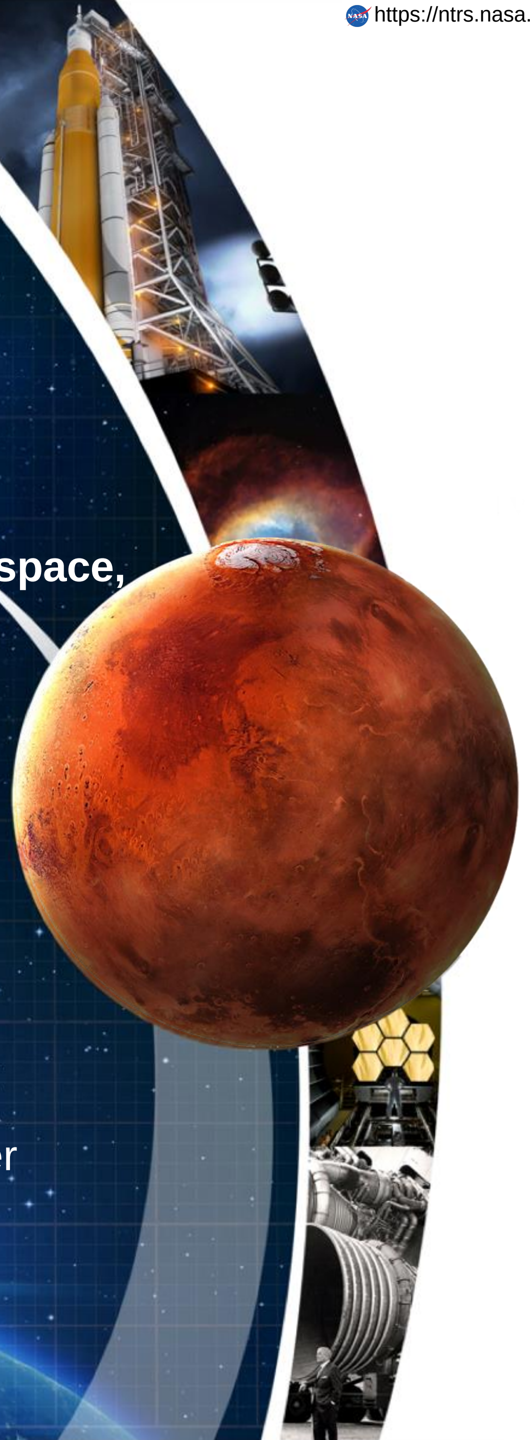
National Aeronautics and Space Administration

Overview of Additive Manufacturing Initiatives at NASA Marshall Space Flight Center - In Space and Rocket Engines



Additive Manufacturing for Aerospace, Defence and Space 2017
February 22-23, 2017
London, United Kingdom

R.G. Clinton, Jr.
Associate Manager, Technical
Science and Technology Office
NASA Marshall Space Flight Center

MARSHALL
SPACE FLIGHT CENTER

Contributors

- Niki Werkheiser: NASA MSFC In Space Manufacturing Program Manager
- Andrew Owens: NASA Tech Fellow, MIT PhD Candidate
- Mike Snyder: Made In Space Chief Designer
- Dr. Tracie Prater: NASA MSFC In Space Manufacturing Materials Characterization Lead
- Kristin Morgan: NASA MSFC Additive Manufacturing Lead
- Elizabeth Robertson: NASA MSFC Additive Manufactured Engine Technology Development

Agenda

- **NASA's In Space Manufacturing Initiative (ISM) For Exploration**
  - In Space Manufacturing Path to Exploration
  - Evolvable Mars Campaign (EMC) Quantitative Benefits Assessment
  - ISM Portfolio
  - ISM Program Timeline
- **Additive Manufacturing (AM) for Rocket Engines**
  - Additive Manufacturing Development for Rocket Engine Space Flight Hardware
  - Engineering And Quality Standard for Additively Manufactured Space Flight Hardware
- **Primary Challenges to Effective Use of Additive Manufacturing**
- **Summary**

Science & Technology Office

In-Space Manufacturing Path to Exploration

NASA

GROUND-BASED

Earth-Based Platform

- Certification & Inspection Process
- Design Properties Database
- Additive Manufacturing Automation
- Ground-based Technology Maturation & Demonstration
- *AM for Exploration Support Systems (e.g. ECLSS) Design, Development & Test*
- *Additive Construction*
- *Regolith (Feedstock)*

EARTH RELIANT ISS

ISS Test-bed Platform

- 3D Print Demo
- Additive Manufacturing Facility
- In-space Recycling
- In-space Metals
- Printable Electronics
- Multi-material Fab Lab
- In-line NDE
- External Manufacturing
- On-demand Parts Catalogue
- Exploration Systems Demonstration and Operational Validation

Space Launch System

PROVING GROUND Cis-lunar

Asteroids

EARTH INDEPENDENT Mars

Planetary Surfaces Platform

- Multi-materials Fab Lab (metals, polymers, automation, printable electronics)
- Food/Medical Grade Polymer Printing & Recycling
- Additive Construction Technologies
- Regolith Materials – Feedstock
- AM Exploration Systems

Text Color Legend

Foundational AM Technologies

AM for Exploration Systems

Surface / ISRU Systems

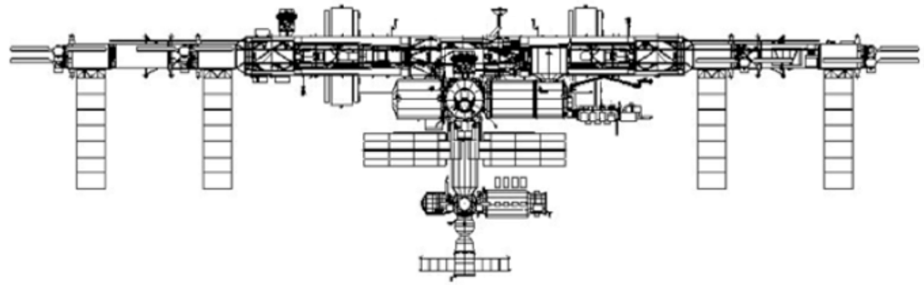
EMC: Maintenance Logistics Models

Each square represents 1000 kg

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

~13,000 kg on orbit

Mass estimates are for mass of spare item only - do not including any packaging or carrier mass



~3,000 kg Upmass per year

Predicted Annual Average Upmass 2012-2020

Corrective Maintenance	*= 1,260 kg*
Preventive Maint. / Consumables	*= 1,930 kg*
Total	*= 3,190 kg*

Expected Average Annual Failures = 450 kg*

Total Approx. Spares Mass Currently Stored On Ground = 17,990 kg

~18,000 kg on ground, ready to fly on demand

This is for a system with:
- **Regular resupply (~3 months)**
- **Quick abort capability**
- **Extensive ground support and redesign/re-fly capability**

* - Based on predicted MTBFs

Cirillo et al. 2011

EMC: Maintenance Logistics Models

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

Mass estimates are for mass of spare item only - do not including any packaging or carrier mass

~95% of all corrective spares will never be used

1000 kg

Impossible to know which spares will be needed

Unanticipated system issues appear, even after years of testing and operation

~3,000 kg Upmass per year

Corrective Maintenance = 1,260 kg

Preventive Maint. / Cons

Total

Expected Average Annual Failures* = 450 kg

Large complement of spares required to ensure crew safety

Total Approx. Spares Mass Currently Stored On Ground = 17,990 kg

~18,000 kg on ground, ready to fly on demand

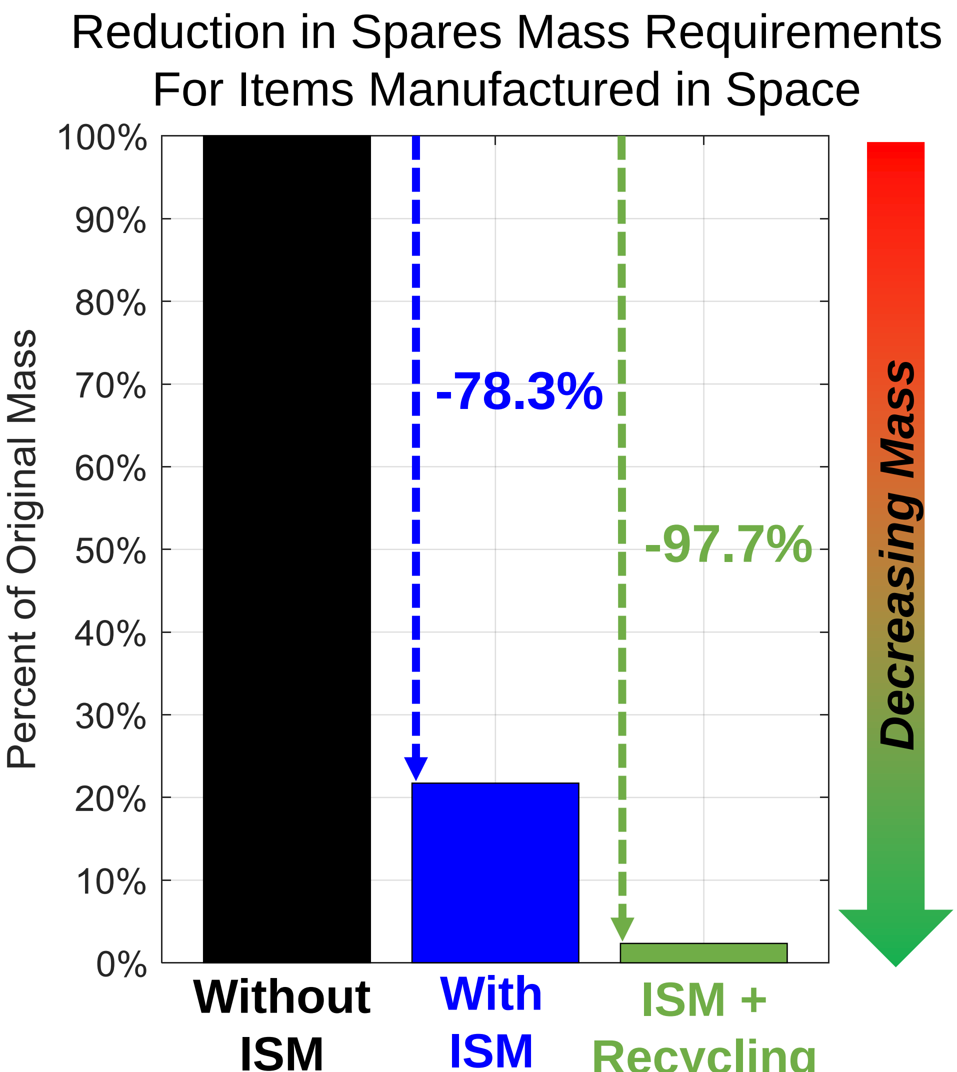
This is for a system with:

- Regular resupply (~3 months)
- Quick abort capability
- Extensive ground support and redesign/re-fly capability

Current maintenance logistics strategy
will not be effective for long-duration missions beyond LEO

Cirillo et al. 2011

EMC: ISM Provides Solutions



This case examined parts associated with fluid flow (i.e. fans, valves, ducts, piping, etc.). Approx. 1/3 of total components were assumed to be manufactured in-space.

ISM significantly reduces the mass that needs to be carried to cover maintenance demands by enabling on-demand manufacturing from common raw materials

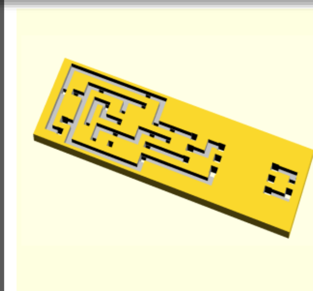
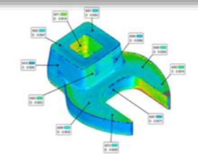
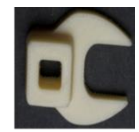
ISM enables the use of recycled materials and in-situ resources, allowing even more dramatic reductions in mass requirements

ISM enables flexibility, giving systems a broad capability to adapt to unanticipated circumstances. This mitigates risks that are not covered by current approaches to maintainability.

In-Space Manufacturing is a strong solution to maintenance logistics challenges that can
- **Reduce mass**
- **Mitigate risk**
- **Enable adaptable systems**

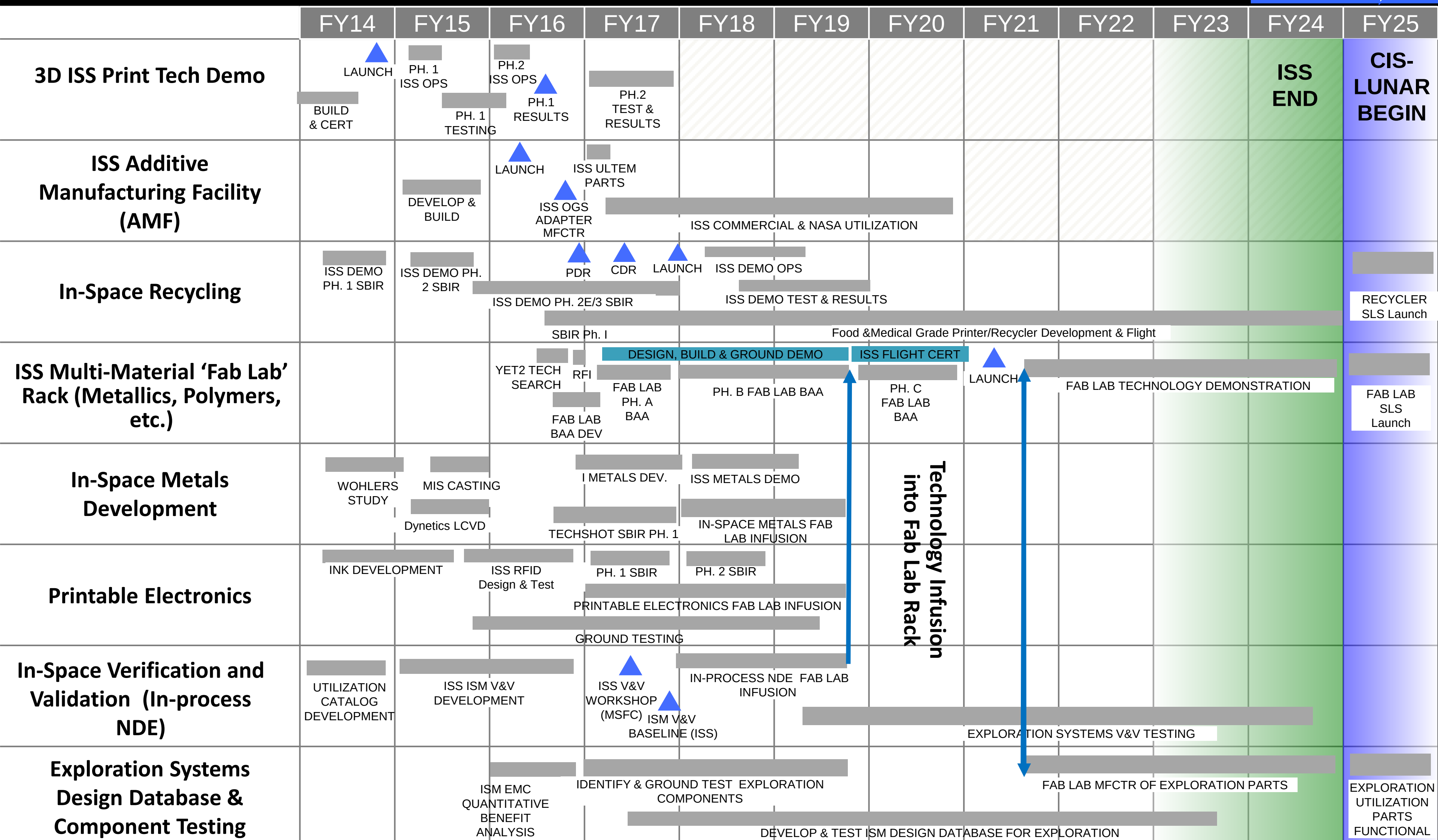
Owens and de Weck 2016

In-Space Manufacturing Portfolio

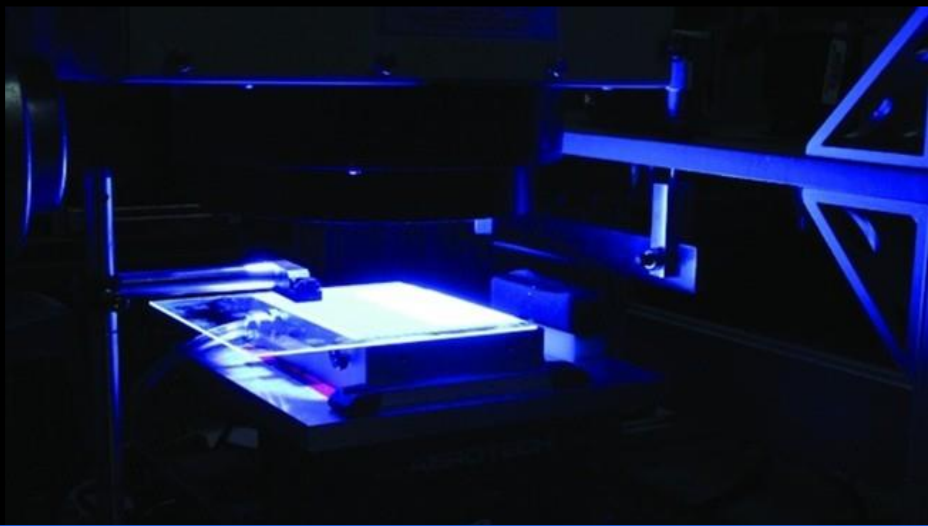
IN-SPACE POLYMERS	IN-SPACE RECYCLING	MULTI-MATERIAL 'FAB LAB' RACK	PRINTED ELECTRONICS	IN-SPACE V&V PROCESS	EXPLORATION DESIGN DATABASE & TESTING (In-transit & Surface Systems)
 	 			 	 
• ISS On-demand Mfctr. w/polymers. • 3D Print Tech Demo • Additive Manufacturing Facility with Made in Space, Inc. • Material Characterization & Testing	• Refabricator ISS Demo with Tethers Unlimited, Inc. (TUI) for on-orbit 3D Printing & Recycling. • Multiple SBIRs underway on common-use materials & medical/food grade recycler	• Develop Multi-material Fabrication Laboratory Rack as 'springboard' for Exploration missions • In-space Metals ISS Demo • nScrypt Multi-material machine at MSFC for R&D	• MSFC Conductive & Dielectric Inks patented • Designed & Tested RFID Antenna, Tags and ultra-capacitors • 2017 ISM SBIR subtopic • Collaboration w/Ames on plasma jet technology.	• Develop & Baseline on-orbit, in-process certification process based upon the DRAFT Engineering and Quality Standards for Additively Manufactured Space Flight Hardware	• Develop design-level database for applications • Materials dev. & characterize for feedstocks (in-transit & surface) in MAPTIS DB. • Design & test high-value components for ISS & Exploration (ground & ISS)

In-Space Manufacturing Program Timeline

Transition to 'Proving Ground'



ISM must influence Exploration design now & develop the corresponding technologies.



Additive Manufacturing

at Marshall Space Flight Center

Additive Manufacturing Development for Rocket Engine Space Flight Hardware

Why invest in Additive Manufacturing (AM) for Propulsion Systems?

Because of the potential it has to

Reduce:

Development Cost

Development Time

Production Time

Recurring Cost

- Surpass traditional manufacturing techniques for certain applications
- Decrease costs and lead times
- Improve performance (Higher strengths than castings; enables unique design solutions; etc.)

3 Tiers of Leveraging AM

- Replace existing part/component design
- Design for additive
- **Develop with additive**

Increase:

Design Flexibility

Reliability

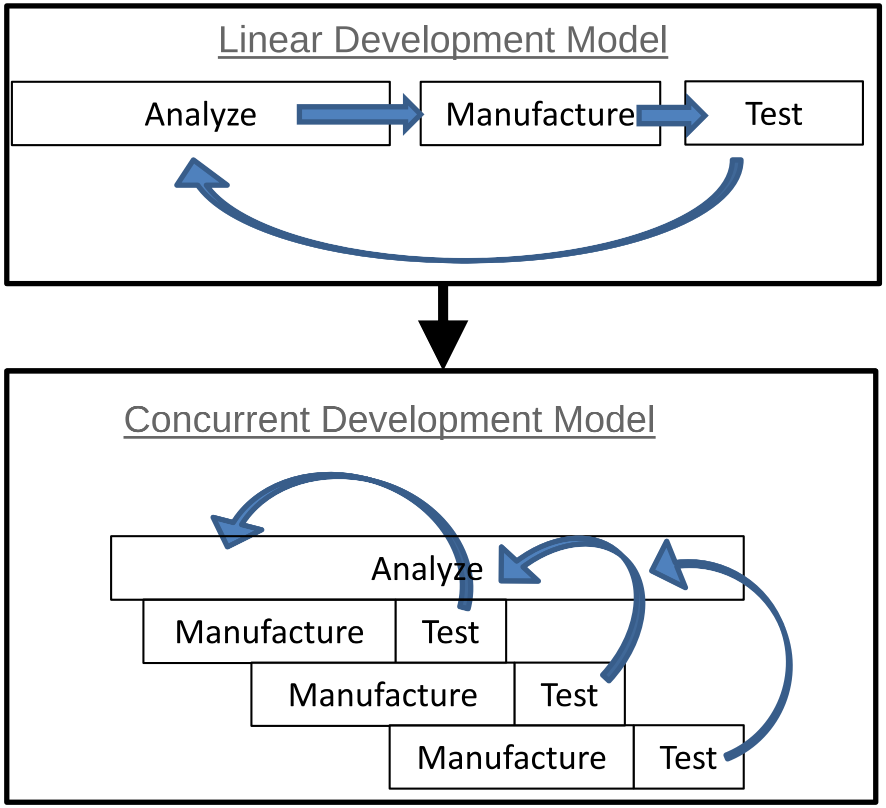
Performance

Test-Fail-Fix Cycles

Additive Manufacturing Demonstrator Engine (AMDE) Project Objectives

Primary Objectives:

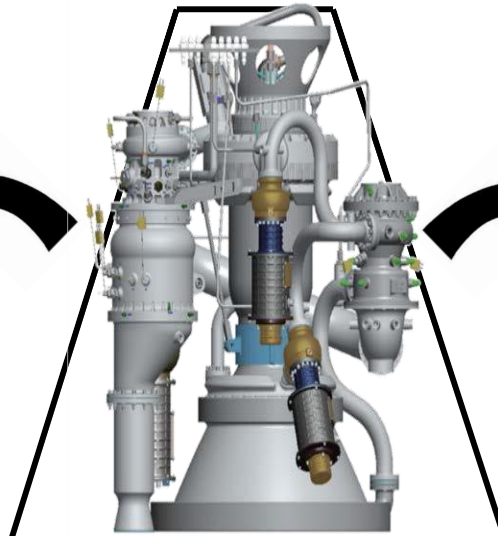
1. Demonstrate an approach that reduces the cost and schedule required for new rocket engine development
   - **Prototype engine in 2.5 years**
   - Operate lean
   - Shift to Concurrent Development
     – Use additive manufacturing (AM) to facilitate this approach
2. Advance the TRL of AM parts through component/system testing
3. Develop a cost-effective Upper-Stage or In-Space Class prototype engine



AMDE Strategic Vision for Future AM Engine Systems

Defining the Development Philosophy of the Future

- **Dramatic Reduction in Design Development, Test and Evaluation (DDT&E) Cycles**
- **Transforming Manual to Automated Manufacturing**
- **3D Design Models and Simulations Increase Producibility**
- **Integrating Design with Manufacturing**



Bridging the gap between the present and future projects that are coming

Building Experience Developing "Smart Buyers" to enable Commercial Partners

Building Foundational Industrial Base

DIRECTEDMFG AS9100B Certified

INCODEMA SHAPING THE FUTURE

MORRIS TECHNOLOGIES Precision. Innovation. Expertise.

SOLID CONCEPTS®

LINEAR MOLD & ENGINEERING

RPM INNOVATIONS, INC.

Transferring "Open Rights" SLM Material Property Data & Technology to U.S. Industry

Enabling & Developing Revolutionary Technology

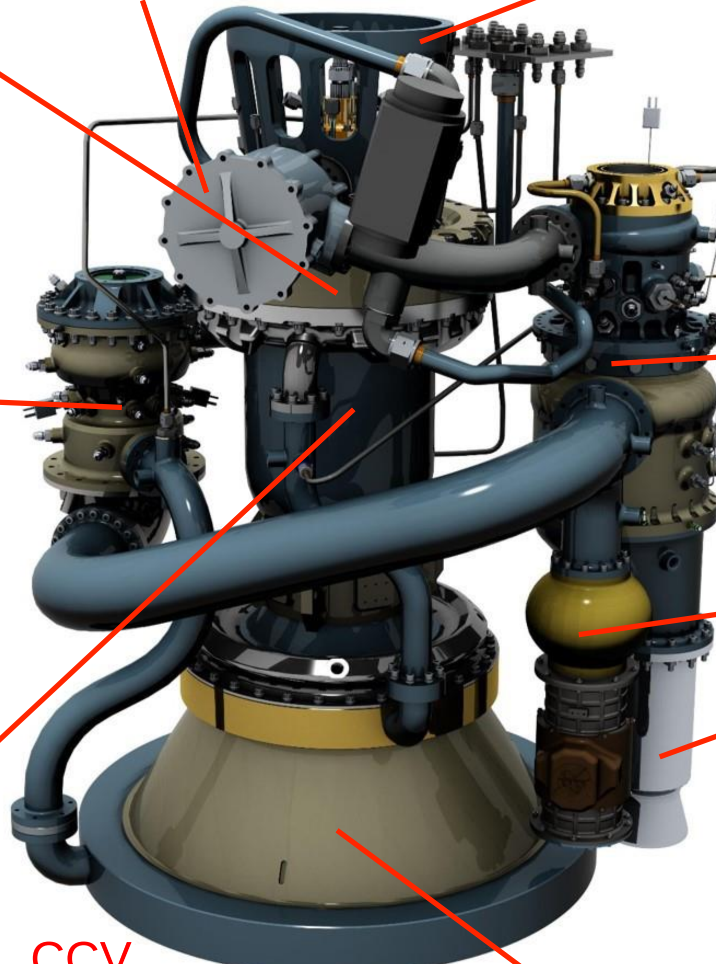
Science & Technology Office

AMDE Reduced Part Count for Major Hardware

Injector
- Decreased cost by 30%
- Reduced part count: 252 to 6
- Eliminated critical braze joints
- Unique design features

FTP
- Schedule reduced by 45%
- Reduced part count: 40 to 22
- Successful tests in both Methane and Hydrogen
- Mass: 90% AM

MCC
- Methane test successful
- Electron Beam Free Form
- Schedule reduction > 50%
- SLM with GRCop.
- Fabrication nickel alloy structural jacket and manifolds.



- <30 welds vs 100+ traditionally
- Compressed Development Cycle 3 years vs. 7
- Reduced part counts
- Invested $10M, 25FTE over 3 years
- Estimated production & test cost for hardware shown $3M

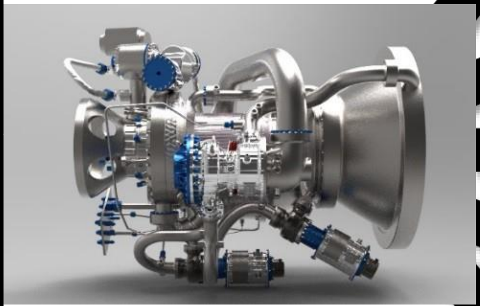
Future Outlook

Fundamental Additive Manufacturing M&P Development

Material Properties & NDE → Standards & Specs → Certification Rationale

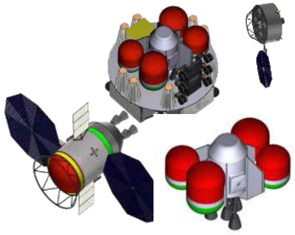
Lean Component Development

Component Relevant Environment Testing



AMDE Prototype Engine

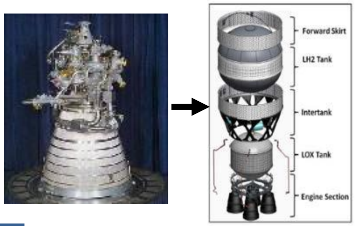
Methane Prop. Systems



CCP

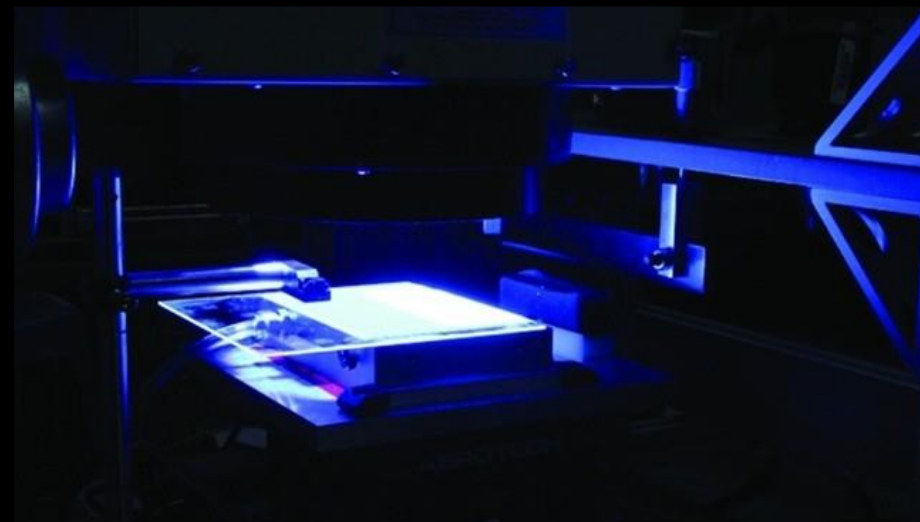
Nuclear Propulsion

Upper Stage Engine



RS-25

Building Foundational Additive Manufacturing Industrial Base



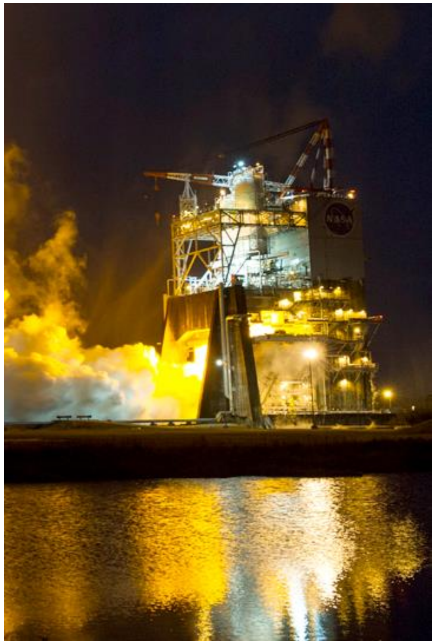
Additive Manufacturing

at Marshall Space Flight Center

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

AM in the Human Exploration and Operations Portfolio

Exploration Systems Development
ORION and SLS



Commercial Crew Program (CCP)
DRAGON V2

NASA Exploration Programs and Program Partners have embraced AM for its affordability, shorter manufacturing times, and flexible design solutions.

13 AM parts are baselined for spaceflight hardware. 40 AM parts are in tradespace.

Science & Technology Office

AM Qualification and Certification at NASA

SpaceX's AM SuperDraco Engine

Program partners in crewed space flight programs (Commercial Crew, SLS and Orion) are actively developing **AM parts scheduled to fly as early as 2018.**

NASA cannot wait for national Standard Development Organizations to issue AM standards.

- In response to request by CCP, MSFC AM Standard drafted in summer 2015.
- Draft standard completed extensive peer review in Jan 2016.
- Final revision currently in work; target release date of Feb 2017.
- **Standard methodology adopted by CCP, SLS, and Orion.**
- Continuing to watch progress of standards organizations and other certifying Agencies.
- Goal is to incorporate AM requirements at an appropriate level in Agency standards and/or specifications.

National Aeronautics and Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

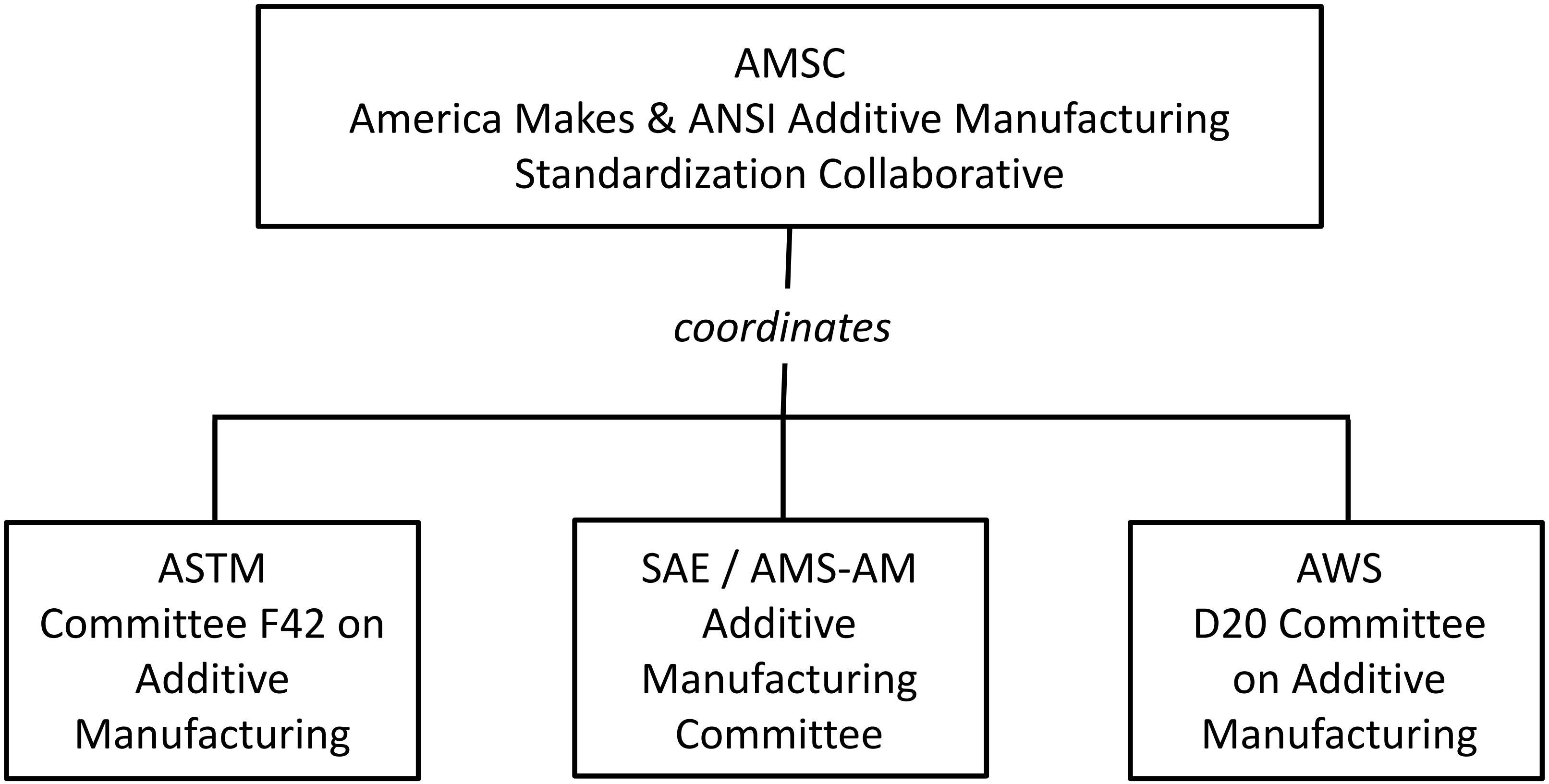
CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

Target release date: February 2017

Standardization is needed for consistent evaluation of AM processes and parts in critical applications.

Relationships among AM Standards Development Organizations

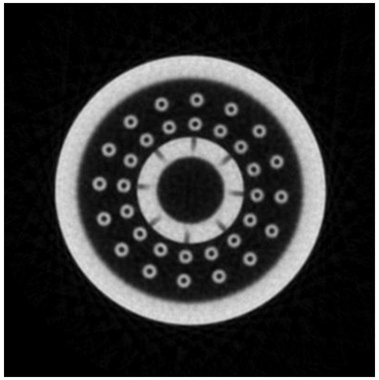


(MMPDS, NADCAP, and CMH-17 are also active)

Process Control Requirements

Draft NASA MSFC Standard implements four fundamental aspects of process control for AM

Metallurgical Process Control



Part Process Control

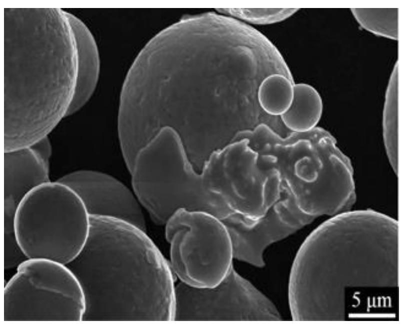
Equipment Process Control

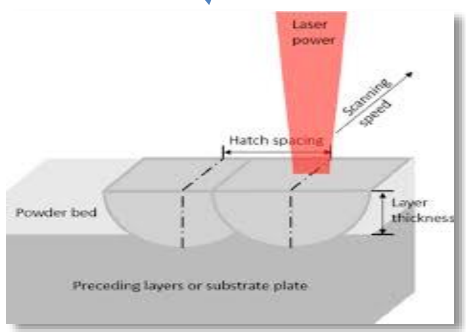
Build Vendor Process Control

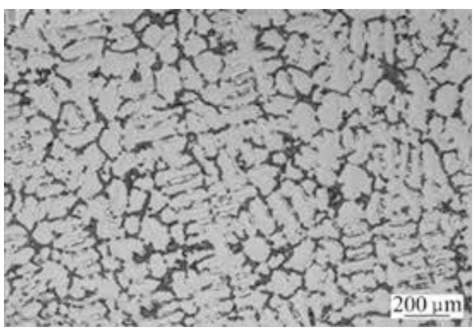
- Process control is central to the 1) qualification of AM processes and parts and 2) certification of the systems in which they operate.
- The standard provides a consistent framework for these controls and provides a consistent set of review/audit products

Metallurgical Process Control

The standard identifies AM as a unique material product form and requires the metallurgical process to be qualified on **each** AM machine.







Powder
- Manufacturing Method
- Chemistry
- Particle Size Distribution
- Contamination
- Recyclability

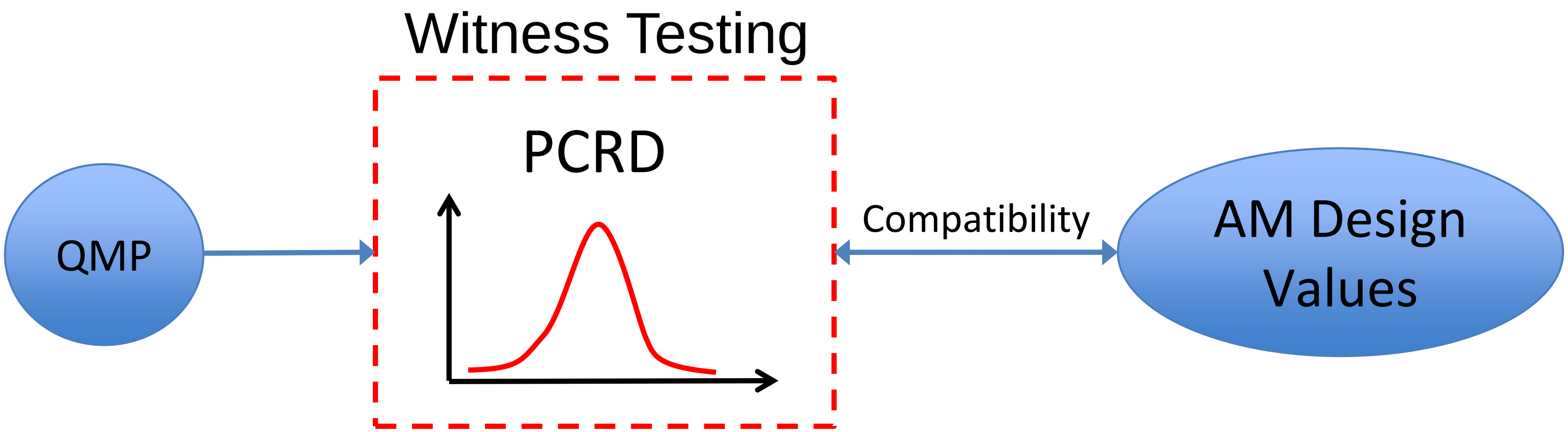
Process Variables
- Fusion Process Parameters
- Chamber Environment
- Consolidation
- Surface finish
- Detail Resolution

Microstructure
- Defect State
- Thermal process – stress relief, HIP, heat treatment
- Microstructural Evolution

Properties
- Process Control Reference Distributions
- DVS registration properties

Material Properties and SPC

- Shift emphasis away from exhaustive, up-front material allowables program intended to account for all process variability (e.g. MMPDS)
- Establish estimates of mean value and variation associated with mechanical performance (tensile and fixed-load fatigue) for the controlled AM process
- Use knowledge of process performance to establish witness test acceptance criteria



Part Classification Criteria

- Part classification is highly informative to part risk, fracture control evaluations, and integrity rationale.

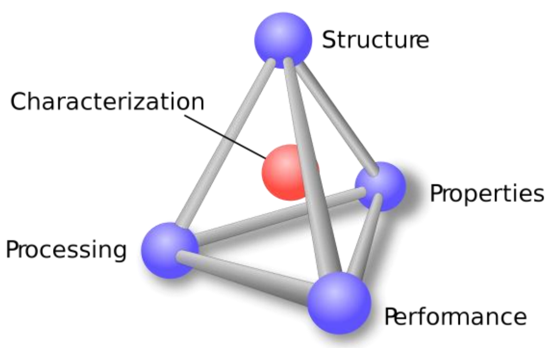
- All AM parts are placed into a risk-based classification system to communicate risk and customize requirements.

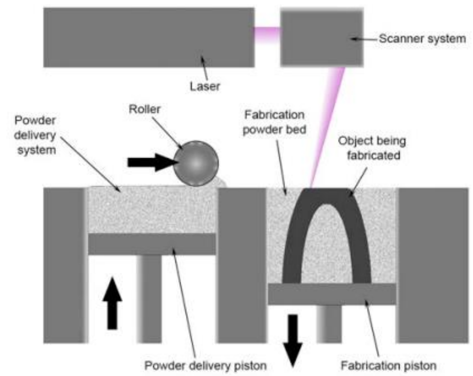
Three decision levels

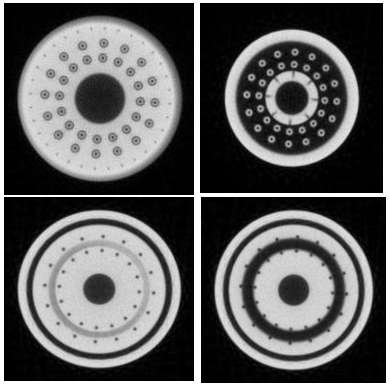
1. Consequence of failure (High/Low) {Catastrophic or not}
2. Structural Margin (High/Low) {strength, HCF, LCF, fracture}
3. AM Risk (High/Low) {Integrity evaluation, build complexity, inspection access}

Primary Challenges to Effective Use of AM

Material Relationships (Understanding the basics)	In-Process Controls (Controlling what you do)	Post-Process Controls (Evaluating what you get)







Challenge: Understanding of the AM process-structure-properties-performance relationships (in operational environments) is necessary for critical applications, yet also costly and time-consuming. Few data are available in open literature. Commercial AM adopters tend to hold their relationship data as IP.

Challenge: AM is an emerging and evolving technology with virtually no process history apart from extrapolation to weld and/or casting methods. Understanding AM process failure modes and effects, identifying observable metrics, and establishing process witnessing methods is essential to part reliability.

Challenge: AM parts with as-built surface roughness, non-uniform grain structure, and/or internal surfaces challenge the capability of standard NDE methods. Quantified NDE methods for AM material and feature must be established in support of NASA's damage tolerance qualification methods.

Part reliability rationale comes from sum of materials relationships, in-process, and post-process controls. Weakness in one must be compensated by the others.

Beyond these challenges, In-Space Manufacturing faces the additional obstacles of: (1) remote operations; (2) microgravity environment; (3) no NDE capability currently on ISS.

Summary: In-Space Manufacturing (ISM)

- **Evolvable Mars Campaign Quantitative Benefits Assessment Conclusions**
  - ISM is a necessary paradigm shift in space operations, not a ‘bonus’
  - Applications should look at recreating function, not form
  - ISM is a capability, not a subsystem, and has broad applications
- **In-space manufacturing is an essential element of the capability suite needed to support NASA’s deep space exploration missions**
  - Reliability increase
  - Logistics reduction (make it or take it)
  - Recycling capabilities
  - Design flexibility
- **NASA has taken the first step towards in-space manufacturing capability by successfully demonstrating 3D print technology on ISS**
- **The journey through development and proving ground trials is a long one**
  - Foundational technologies are yet to be demonstrated
  - Design for repair culture needs to be embraced
  - Applications need to be validated in operational environment
  - ISS is a critical testbed for demonstrating technologies and validating capabilities

To have functional capability supporting Exploration timeline, ISM must work with Exploration systems designers now to identify high-value application areas and influence process.

Summary: Additive Manufacturing of Rocket Engines for Space Exploration

- **Additive Manufacturing Demonstrator (AMDE) is a pathfinder and catalyst for culture change in design and development of future rocket engines.**
  - Demonstrated game changing aspects of cost and schedule reduction
  - Dramatic impacts on Design, Development, Test and Evaluation (DDT&E) cycle time reduction and philosophy
  - Established technology testbed and prototype for future Exploration Upper Stage or In-Space class engines
- **Certification approach for additively manufactured rocket engine components developed by MSFC defines the expectations for engineering and quality control in developing critical AM parts**
  - Additively manufactured components do not require a unique certification approach
  - Standard allows innovation while managing risk
  - Final revision target release date is February 2017
  - Standard methodology adopted by CCP, SLS, and Orion
  - Standard methodology framework being adapted for ISM

Standardization is needed for Additive Manufacturing process qualification, part certification and risk assessments.